IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers

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Abstract: Technical information is provided related to liquid-immersed power transformers insulated with high-temperature materials. Guidelines for applying existing qualified high-temperature materials to certain insulation systems, recommendations for loading high-temperature liquid-immersed power transformers, and technical information on insulation-system temperature ratings and test procedures for qualifying new high-temperature materials are included.
Keywords: high-temperature insulation material, hybrid insulation system, liquid-immersed power transformer, loading guide

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

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Introduction

(This introduction is not part of IEEE Std 1276-1997, IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers.)

Liquid-immersed transformers utilizing high-temperature insulation systems are being used increasingly by the industry, and current standards do not effectively cover their performance criteria. This guide is intended to give the user some background information on the application and use of high-temperature insulation in power transformers.

The highest allowable temperature of the transformer winding insulation is an essential parameter in determining the maximum load that a transformer may reliably carry. If the allowable winding hottest-spot temperature may be increased, the weight and size of a power transformer may be significantly reduced while maintaining the same rated power, or, for the same size unit, the allowable power output may be increased. However, the user must understand the consequences of allowing the transformer temperature to exceed the material's accepted limits. The operating life of conventional insulating materials—namely, paper, transformerboard, and mineral oil—is dependent upon the operating temperature and the contaminants, including moisture, in the transformer.

Existing transformer standards specify the maximum allowable winding hottest-spot temperature on the basis of an acceptable normal insulation life. A relationship between temperature and degradation of the dielectric insulation has been established in IEEE Std C57.91-1995. From this relationship, the loss of insulation life due to a temporary or permanent loading beyond normal operating temperatures may be calculated. The actual life of a transformer depends only indirectly on the thermal aging of solid insulation materials. Laboratory tests of cellulose materials (i.e., paper and transformerboard) have demonstrated that overheating can significantly reduce their tensile strength with only a slight reduction in dielectric strength. Therefore, a likely failure mode caused by overheating of the cellulose is the mechanical breakdown of embrittled insulation during a high-current fault, which can lead to a dielectric breakdown of the damaged insulation. This phenomenon may hold for other insulating materials as well.

One method of reducing the weight and size of a liquid-immersed transformer without sacrificing its life or reliability is the use of materials with higher temperature capability. The first step in this direction was made some 40 years ago when thermally upgraded cellulose was developed for transformer insulation. This technological improvement increased the rated power of liquid-immersed transformers by 12%, allowing the average winding rise to increase from 55 °C to 65 °C.[*]

During the last 30 years, materials with even higher temperature capability, such as aramid papers and transformerboards and high-temperature enamels, have been developed. To date, these materials have been used in some specialty transformers, such as traction or mobile units, and some have been used to uprate liquid-immersed transformers rebuilt after a failure. There are potential applications for new transformers using these high-temperature insulation materials. For example, instead of installing a cellulosic-insulated transformer with a rating equal to the overloads, a smaller-rated unit with high-temperature insulation materials can be installed that can withstand the desired overload.

It is important to note that high-temperature insulation materials must meet a number of criteria to be suitable for use in power transformers. They must operate at elevated temperatures in transformer oil while maintaining their mechanical and dielectric properties. They must also demonstrate compatibility with all other components of the transformer, as well as have suitable characteristics for the mechanical stresses encountered in a power transformer, such as adequate compressive strength.

[*]Discussions of 55 °C rise systems are included in this guide for historical reference only.

Combining high-temperature and cellulosic materials to form a hybrid high-temperature insulation system is another viable option. This hybrid insulation system is usually composed of high-temperature materials adjacent to winding conductors, where temperatures are hottest, with cellulose-based materials in other areas. This insulation system is possible because only insulation material in direct contact with the winding conductors, and perhaps the core, is exposed to the highest temperatures, while other parts of the insulation system operate at lower temperatures. To date, only aramid papers, aramid transformerboards, and high-temperature enamels in combination with cellulose have been used in this type of hybrid insulation system.

From the point of view of thermal aging, cellulose has been the limiting factor of traditional insulation systems composed of mineral oil, cellulose, and enamel. With the advent of high-temperature solid insulating materials, mineral oil becomes the limiting factor, establishing the highest allowable temperature of the insulation system. Other insulating fluids have been examined for the possible replacement of mineral oil, and many are used in applications where their dielectric and physical properties meet the needs of those applications. Until now there have been few instances where these other insulating fluids have been used in power transformers above 30 MVA. Certain fluids, such as silicones, high molecular weight hydrocarbons, non-PCB chlorinated hydrocarbons, polyolefins, and ester-based fluids, may offer particular advantageous characteristics for specific applications.

Future research may identify new fluids with broader applications for use in power transformers that can operate at higher temperatures due to high-temperature insulating materials. Other factors to consider when designing units that operate at high temperatures are, for example, load losses, tap changers, bushings, control wiring, paint, and adhesives.

Participants

At the time this guide was completed, the Working Group on High-Temperature Insulation for Liquid-Immersed Power Transformers had the following membership:

Michael A. Franchek, *Chair*

J. Arteaga
J. Aubin
R. L. Barker
M. F. Barnes
D. Chu
J. L. Corkran
V. Dahinden
R. C. Degeneff
D. Dohnal
M. L. Frazier
D. F. Goodwin
J. L. Goudie
R. L. Grubb
P. J. Hopkinson
V. C. Jhonsa
E. W. Kalkstein
C. J. Kalra
L. Koga
B. Kumar
M. Y. Lau
S. Lindgren
L. A. Lowdermilk
J. W. McGill
C. J. McMillen
R. E. Minkwitz, Sr.
M. I. Mitelman
E. T. Norton
D. E. Orten
B. K. Patel
G. Payerle
P. A. Payne
T. A. Prevost
G. J. Reitter
S. M. A. Rizvi
M. P. Sampat
H. J. Sim
R. W. Simpson, Jr.
M. R. Springrose
W. W. Stein
T. H. Stewart
C. L. Stiegemeier
R. W. Stoner
R. A. Veitch
L. B. Wagenaar
F. N. Weffer
R. J. Whearty
R. C. Wicks
D. J. Woodcock
F. N. Young

The following persons were on the balloting committee:

Edward J. Adolphson
Paul Ahrens
D. J. Allan
Jim Antweiler
Jacques Aubin
Donald E. Ballard
Ron L. Barker
Mike Barnes
William H. Bartley
Martin Baur
Edward A. Bertolini
Wallace B. Binder
Thomas E. Blackburn, III
William E. Boettger
Alain Bollinger
Joe V. Bonucchi
John D. Borst
Alvaro Cancino
W. J. Carter
C. P. Caruso
Donald J.Cash
Jerry L. Corkran
Domenico E. Corsi
Bob Del Vecchio
Dieter Dohnal
J. C. Duart
Richard F. Dudley
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Keith Ellis
D. J. Fallon
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P. T. Feghali
Joe Foldi
S. Foss
Ron Fox
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Donald A. Gillies
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Blaine Gremillion
Robert L. Grubb
Robert L. Grunert
Geoff H. Hall
Ernst Hanique
N. Wayne Hansen
J. W. Harley
James H. Harlow
Robert H. Hartgrove
R. R. Hayes
William R. Henning
K. R. Highton
Peter J. Hoefler
T. L. Holdway
Philip J. Hopkinson
Richard Huber
James D. Huddleston, III
A. F. Hueston
Virendra Jhonsa
Anthony J. Jonnatti
Lars-Erik Juhlin
Edward W. Kalkstein
Gene Kallaur
Joe J. Kelly
Sheldon P. Kennedy
Lawrence A. Kirchner
Brian Klaponski
Egon Koenig
L. Koga
Barin Kumar
John G. Lackey
Michael Y. Lau
J. P. Lazar
Singson Lee
Frank A. Lewis
Thomas Lundquist
Joe D. MacDonald
William A. Maguire
Charles Mandeville
Jose R. Marotta
K. T. Massouda
John W. Matthews
L. Bruce McClung
Charles J. McMillen
Nigel P. McQuin
C. Patrick McShane
Sam P. Mehta
Joe Melanson
Sam Michael
Russell E. Minkwitz, Sr.
Michael I. Mitelman
Daleep Mohla
Harold R. Moore
Steve Moore
Daniel H. Mulkey
Chuck R. Murray
R. J. Musil
William H. Mutschler, Jr.
Larry Nunnery
T. V. Oommen
Gerald A. Paiva
Klaus Papp
B. K. Patel
Dhiru S. Patel
Wesley F. Patterson
Jesse M. Patton
George Payerle
Dave Payne
Paulette A. Payne
Carlos Peixoto
Dan D. Perco
Mark D. Perkins
Trevor Pfaff
Linden W. Pierce
R. Leon Plaster
Donald W. Platts
Tom A. Prevost
Richard Provost
Jeewan L. Puri
Stephen C. Pyke
George J. Reitter
J. C. Riboud
Peter G. Risse
Chris A. Robbins
Arlise L. Robinson, Jr.
David J. Rolling
John R. Rossetti
Hazairin Samaulah
Mahesh P. Sampat
V. S. N. Sankar
Subhas Sarkar
Rick Sawyer
William E. Saxon
Pat Scully
Hyeong Jin Sim
R. William Simpson, Jr.
Pritpal Singh
Tarkeshwar Singh
James E. Smith
J. Ed Smith
Leonard R. Smith
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Gary Sparagowski
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Robert W. Thompson
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Edger R. Trummer
Subhash C. Tuli
Robert R. Turcotte, Jr.
John Vandermaar
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Robert A. Veitch
Loren B. Wagenaar
Ralph D. Wakeam
Barry H. Ward
Robert Whearty
Roger Wicks
A. L. Wilks
William G. Wimmer
F. N. Young
Peter Zhao

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IEEE Guide for the Application of High-Temperature Insulation Materials in Liquid-Immersed Power Transformers

1. Overview

The intent of this guide is to provide information on the application and use of high-temperature insulation in liquid-immersed power transformers. It addresses only those areas where the application and use differ from the existing standards for these types of transformers.

1.1 Scope

This guide provides technical information related to liquid-immersed power transformers insulated with high-temperature materials.

— Guidelines are provided for applying existing qualified high-temperature materials to insulation systems suitable for high-temperature liquid-immersed power transformers.

— Recommendations are made regarding the loading of high-temperature liquid-immersed power transformers.

— Technical information is provided for insulation-system temperature ratings and test procedures for qualifying new high-temperature materials as they become available.

No specific guidance is provided on insulating fluids other than mineral oil. This subject is to be covered in a future revision of this guide once more field experience is available using fluids other than mineral oil in combination with high-temperature solid materials.

1.2 Purpose

This guide is intended as a first step in the direction of standardizing the application of high-temperature insulation systems in transformers using insulation materials such as aramid papers, aramid transformerboards, high-temperature enamels, and hybrid systems that include both high-temperature materials and cellulose materials. It provides technical information for the transformer designer as well as for the transformer user.

2. References

This guide should be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the latest revision shall apply.

IEEE Std C57.12.00-1993, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers (ANSI).[1]

IEEE Std C57.12.90-1993, IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers, and IEEE Guide for Short-Circuit Testing of Distribution and Power Transformers (ANSI).

IEEE Std C57.91-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers (ANSI).

IEEE Std C57.100-1986 (Reaff 1992), IEEE Standard Test Procedures for Thermal Evaluation of Oil-Immersed Distribution Transformers (ANSI).

IEEE Std C57.104-1991, IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers (ANSI).

3. Definitions

This clause defines terms as they are used in this guide. The term “transformer” refers to liquid-immersed power transformers, unless an alternate meaning is specified.

3.1 aramid: A manufactured material in which the base polymer is a long-chain synthetic polyamide with at least 85% of the amide linkages attached directly to two aromatic rings. Paper and transformerboard are made from this material and have been shown to be suitable for use in high-temperature and hybrid high-temperature insulation systems.

3.2 average winding temperature: The average temperature of the winding as determined from the ohmic resistance measured across the terminals of the winding, in accordance with the cooling curve procedure specified in IEEE Std C57.12.90-1993.

3.3 average winding temperature rise ($\Delta\theta_w$): The arithmetic difference between the average winding temperature and the average temperature of the air surrounding the transformer. Also, “rise,” unless otherwise stated, will refer to the average winding temperature rise.

3.4 cellulose: The term “cellulose,” unless otherwise stated, refers to unbleached kraft insulation material from which paper and transformerboard are made, that is suitable for use in 65 °C average winding temperature rise insulation systems.

3.5 high-temperature: Used to describe materials, insulation systems, and transformers that are designed to operate at a maximum hottest-spot temperature above 120 °C.

3.6 high-temperature insulation system: An insulation system composed of all high-temperature solid insulation materials, with or without high-temperature fluids.

[1]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

3.7 hottest-spot differential temperature: The temperature difference between the hottest spot of the conductors in contact with insulation and the average winding temperature.

3.8 hybrid high-temperature insulation system: An insulation system usually composed of high-temperature solid insulation material adjacent to winding conductors and cellulose materials in the areas where the maximum temperature at rated load does not exceed 120 °C. This system typically uses conventional mineral oil as the insulating liquid.

3.9 insulation system: A system composed of solid insulating materials and insulating fluid. Synonym: system.

3.10 maximum hottest conductor temperature: Used in discussions involving the life testing of materials, in lieu of the phrase winding hottest-spot temperature ($\theta_{h)}$.

3.11 mobile transformer: Transformers that are usually mounted on trailers for easy transport to temporarily replace stationary transformers taken out of service because of failure or maintenance.

3.12 normal insulation life: The time span during which the process of material decomposition reaches a benchmark as described in 5.3, Table 2, of IEEE Std C57.91-1995.

3.13 system: See: insulation system.

3.14 transformerboard: Pressboard specifically manufactured for use as transformer dielectric insulation.

4. Merits of operating at high temperatures

For given quantities of active materials (core steel and conductor), the throughput of the transformer can be increased if the allowable average winding temperature rise is increased beyond the 65 °C rise insulation system limit.

NOTE—For a transformer, percent reactance increases proportionally with the rated power throughput (MVA). Load losses increase in proportion to the MVA ratio squared, with an additional increase due to increased conductor resistance at the elevated temperature.

As examples, Figures 1 and 2 illustrate the merits of increasing the average winding temperature rise over average oil temperature ($\Delta\theta_{w/o}$) for two particular transformer design families. Figure 1 expresses the relationship between transformer capacity increase and $\Delta\theta_{w/o}$, while Figure 2 shows the relationship between reduced core and coil weight and $\Delta\theta_{w/o}$.

Most modern transformers operate with a relatively low $\Delta\theta_{w/o}$. Therefore, a small increase in $\Delta\theta_{w/o}$ can yield a significant increase in the transformer rating for a given weight, or a decrease in transformer weight for a given rating.

5. Insulation-system temperature ratings, test procedures, and material aging qualification

5.1 Insulation-system temperature ratings for 55 °C[2] and 65 °C rise systems

Cellulose-based insulation systems have been grouped into two temperature rise classes, 55 °C and 65 °C. They denote the highest permitted average winding rise over a standard average daily ambient temperature

[2]Discussions of 55 °C rise systems are included in this guide for historical reference only.

of 30 °C. Although the bulk of the insulation between conductors will experience a degree of degradation related to the average winding temperature, the maximum degradation occurs in the insulation that is in

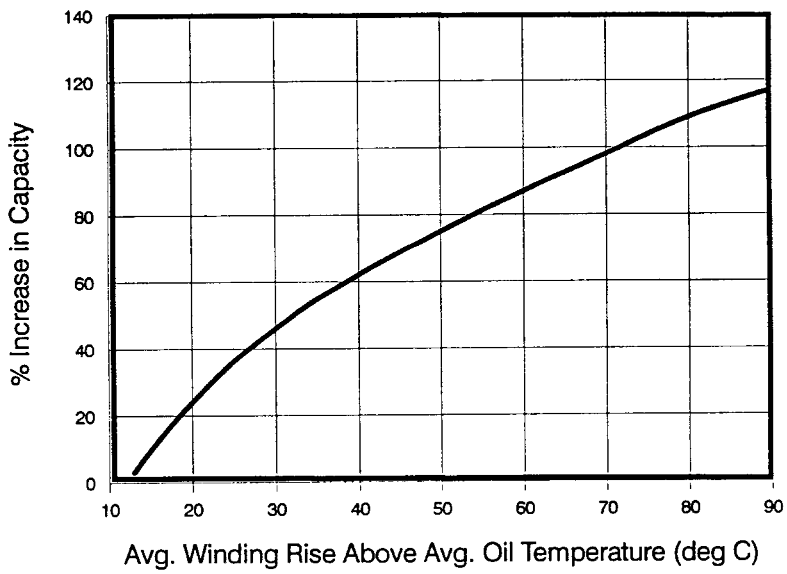

Figure 1—Relationship between transformer capacity increase and $\Delta\theta_{w/o}$

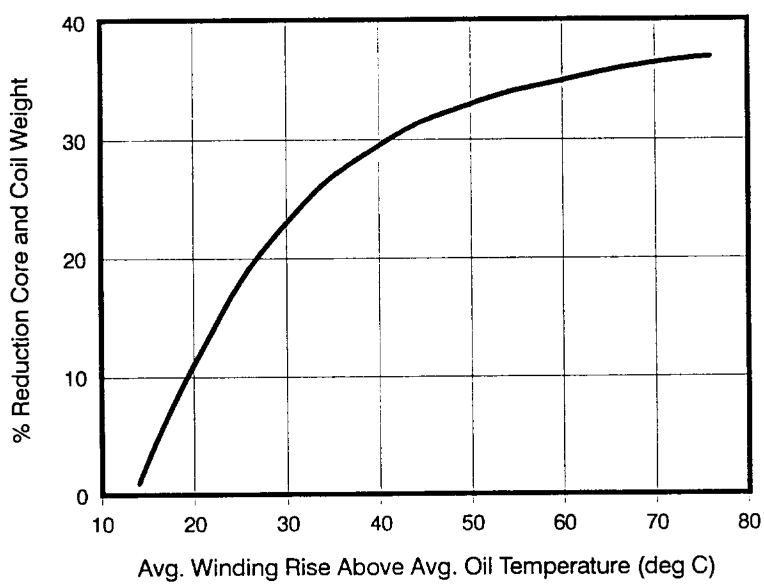

Figure 2—Relationship between reduced core and coil weight and $\Delta\theta_{w/o}$

contact with the conductors at the highest local, or "hottest spot," temperature existing within the winding. This winding hottest-spot temperature is calculated as the sum of

— The ambient temperature (θ_a) of 30 °C averaged over a 24-h period, with a maximum ambient of 40 °C during the period, according to IEEE Std C57.91-1995

— The average winding rise over the ambient temperature ($\Delta\theta_w$)

— The winding hottest-spot rise over the average winding temperature rise ($\Delta\theta_{h/w}$)

As an example, for thermally upgraded cellulose, the average winding rise over ambient temperature must not exceed 65 °C, and the sum of the latter two components ($\Delta\theta_w + \Delta\theta_{h/w}$) must not exceed 80 °C, which produces a maximum hottest-spot temperature of 120 °C (65 °C + 40 °C + 15 °C = 120 °C).

Effectively, the highest daily average winding hottest-spot temperature that can be withstood on a continuous basis without excessive loss of life is 110 °C for the upgraded cellulose material (65 °C + 30 °C + 15 °C = 110 °C).

In reality, the highest winding hottest-spot temperature is seldom sustained over an extended time period. It varies with the load, which is changing in accordance with daily, weekly, monthly, and seasonal cycles. The rate of loss of life is an exponential function of the time that the insulating materials are exposed to the winding hottest-spot temperature. Consequently, the typical life of a power transformer is estimated at some 30 years of service. This 30-year life represents four to five times the normal insulation life, under continuous full-load conditions, for a 65 °C rise insulation system.

5.2 Insulation-system temperature ratings for high-temperature rise systems

Special transformers with 65 °C rise cellulose insulation systems, such as those used in mobile substations, may be rated at 75 °C average winding rise over ambient temperatures. A reduced insulation life expectancy and an increased power rating for a given size and weight of a transformer are acceptable for this application since the transformer is not expected to be in continuous service.

Recently, a 95 °C average winding rise has been used for mobile transformers and for transformers re-engineered during repair that utilize a hybrid insulation system (cellulose and aramid). The allowable top oil temperature in these units has typically been limited to 105 °C, although in some cases, individual users allow the top oil temperature limit to be 110 °C or more (see IEEE Std C57.91-1995, Table 8). The maximum allowable winding hottest-spot temperature (MHCT) has typically been 170 °C, although temperatures up to 190 °C have been used (see Table 1). Operation at these temperatures, which are above the 145 °C flash point of oil, may be justified because the lack of free oxygen in the vicinity of the winding hottest spot reduces the risk of oil ignition. Figure 3 shows that the aramid material has a normal insulation life in oil of 65 000 h and 180 000 h at temperatures of 188 °C and 174 °C, respectively. These values are above the typical winding hottest-spot temperature for a hybrid high-temperature insulation system of 170 °C. There have been instances where winding rises higher than 95 °C, and winding hottest-spot temperatures higher than 170 °C have been used for a specific application.

As with a cellulose insulation system, gases in the form of bubbles may evolve in the hybrid insulation system at higher temperatures. This process is described in Annex A of IEEE Std C57.91-1995 and was investigated by ESEERCO [B1][3] for both cellulose and hybrid insulation systems. It was found that the evolution of gases in both systems depended on the moisture content of the solid insulation. It was also found that at the low moisture contents typical in power transformers, gases began to evolve from the hybrid system at significantly higher temperatures than in a cellulose insulation system. Cellulose in the conventional system may produce decomposition gases at temperatures above 140 °C, while the aramid in the hybrid system typically produces no such gases up to and beyond 220 °C.

[3]The numbers in brackets correspond to those of the bibliography in Annex B.

Transformers with insulation systems containing mineral oil, cellulosic insulation, and high-temperature insulation materials may be rated for temperatures, as is shown in Table 1. The high-temperature rise systems listed in this table are based on industry experience with hybrid insulation systems, as explained in Clause 7 of this guide.

Table 1—Maximum temperature limits for various insulation systems

Insulation system temperatures	65 °C rise system (°C)	Examples of hybrid and high-temperature rise systems (°C)	
Average winding rise over ambient temperature, $\Delta\theta_w$	65	95	115
Winding hottest-spot rise over ambient temperature, $\Delta\theta_{h/a}$	80	130	150
Ambient temperature, θ_a (maximum)	40	40	40
Winding hottest-spot temperature, θ_h (maximum ambient) (MHCT)	120	170	190
Ambient temperature, θ_a (average)	30	30	30
Winding hottest-spot temperature, θ_h (average ambient) (MHCT-10)	110	160	180
Top oil temperature rise over ambient temperature, $\Delta\theta_{to}$	65	65	65
Top oil temperature, θ_{to} (maximum ambient)	105	105	105
Cellulose hottest-spot rise, $\Delta\theta_{hk}$	80	80	80
Cellulose hottest-spot temperature, θ_{hk} (maximum ambient)	120	120	120
$\Delta\theta_w/\Delta\theta_{to}/\Delta\theta_{hk}/\Delta\theta_{h/a}$	65/65/80/80	95/65/80/130	115/65/80/150

5.3 Hybrid high-temperature insulation systems

For most applications requiring high-temperature insulation in liquid-filled power transformers, a hybrid insulation system combining high-temperature insulation with conventional cellulose insulation may be used. High-temperature insulation materials are applied directly to the hottest areas, such as winding conductors, which may be insulated with aramid paper or high-temperature enamel. Aramid transformerboard may be used for oil barriers, radial spacers, and axial spacers that are in direct contact with the transformer windings. Cellulose insulation may be used for winding cylinders, cylindrical high-to-low barriers, phase-to-phase barriers, collars, end rings, cap rings, etc. if the temperature of these components does not exceed 120 °C. These lower-temperature insulation components are typically located in the cooler bulk oil of the transformer. In a transformer with a hybrid insulation system, the same maximum top oil temperature is allowed as in conventional transformers (IEEE Std C57.12.00-1993). A larger temperature differential between top and bottom oil is typically attained by more effective cooling. The designer must make sure that the high-temperature insulation components are used in all areas of the transformer that might be subjected to temperatures above the thermal capability of the lower-temperature components.

For example, some units built using a hybrid insulation system composed of aramid and cellulose have been designed with a 95 °C average winding rise. This average winding rise over a maximum ambient of 40 °C results in an average winding temperature of 135 °C.

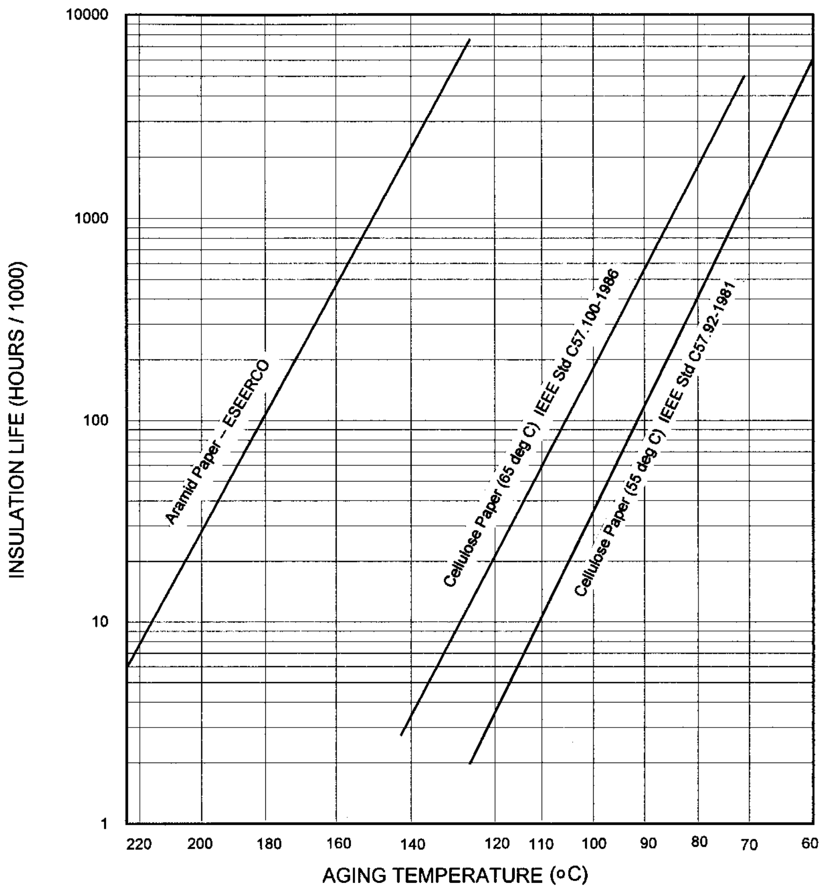

Figure 3—Arrhenius curve for insulation life of cellulose and aramid in oil (based on loss of 50% tensile strength)

In the hybrid insulated transformers, the typical hot-spot differential temperature has been 35 °C, which when added to the average winding temperature gives 170 °C as the hottest-spot temperature of the conductor (95 °C + 40 °C + 35 °C = 170 °C).

In contrast, transformers insulated with thermally upgraded cellulose are designed for a maximum average winding rise of 65 °C. This average winding rise over a maximum ambient of 40 °C results in an average winding temperature of 105 °C. In these transformers, the typical hot-spot differential temperature has been 15 °C, which when added to the average winding temperature gives 120 °C as the hottest spot temperature of the conductor (65 °C + 40 °C + 15 °C = 120 °C).

5.4 Aging test procedure for material qualification

Currently, only aramid papers, aramid transformerboards, and some wire enamels have passed the thermal, electrical, and mechanical tests required for qualification for use in high-temperature liquid-immersed power transformers. In the future, other materials may become available. In order to qualify an insulation material for operation at a specified MHCT, it should be demonstrated that the material retains at least 50% of its initial tensile strength after 65 000 h of aging at the temperature (MHCT-10) °C when tested by the "Standard Test Procedure for Sealed Tube Aging of Liquid-Immersed Transformer Insulation" defined in the

annex of the 1994 revision of IEEE Std C57.100-1986. For wire enamel insulation, the material must retain at least 80% of its initial dielectric strength after 65 000 h of aging at the temperature (MHCT-10) °C.

NOTE—For cellulose, the MHCT is 120 °C, based on an allowable 80 °C winding hottest-spot rise over a maximum ambient of 40 °C. However, the life expectancy is based on a 24-h average ambient of 30 °C.

In addition, for all materials, aging tests must be performed over a sufficiently wide temperature range so that the A and B in Equation (1) may be determined. This equation, from IEEE Std C57.100-1986, for 65 °C cellulose insulation is

$$\text{Life (hours)} = \varepsilon^{(B/\theta - A)} \tag{1}$$

where

A	is 28.082,
B	is 15 000,
ε	is the base of the natural logarithm,
θ	is 273 + (MHCT-10), in °C,
MHCT	is the maximum hottest conductor temperature, in °C.

NOTE—The constants will be different for other materials.

5.5 Aging test procedure for hybrid high-temperature insulation-system qualification

To fully evaluate the thermal capability of new insulation systems, including hybrid insulation systems, it is necessary to establish aging criteria. This may be accomplished by testing insulation-system models designed for accelerated aging of materials commonly used in transformers. The most comprehensive approach is the aging of prototype transformers, but this technique is very expensive and somewhat impractical. A more economical approach relies on the use of small aging cells or tubes containing all of the relevant materials used in transformers. These materials are aged at elevated temperatures to arrive at a thermal life equation for that system. This type of accelerated aging is a problem when trying to age a combination of materials with significantly different thermal capabilities, as in the hybrid system. If the aging is carried out at temperatures high enough to accelerate the aging of the higher-temperature component, it will result in rapid degradation of the lower-temperature components. If the aging is carried out at temperatures suitable for reasonable aging of the lower-temperature components, the higher-temperature materials may require exceedingly long aging times.

An alternative approach to the thermal aging problem of a dual-temperature system is a model designed to allow high-temperature aging of a coil assembly, while allowing the bulk liquid and insulation away from the coil to be maintained at an elevated temperature that is lower than the hot coil. A steel tube containing an immersion heater and thermocouples can be used to maintain and control the bulk liquid temperature. On the cell cover, a coil assembly containing an insulated conductor can be mounted and surrounded by spacer material in the shape of sticks and blocks to simulate an actual winding configuration. A thermocouple on the conductor surface may be used to monitor conductor temperature, independent of the bulk fluid temperature. Temperature may be controlled by adjusting current flow through the insulated conductor.

The coil may be connected to an external power source that has current control for precise temperature stability. A small piece of core steel should be placed in the cell, with bulk insulation pieces arranged around the periphery of the cell to simulate bulk components such as end blocks, structural supports, winding cylinders, angle rings, and static rings. All materials in the cell should be in volume ratios closely simulating the ratios in a typical liquid-immersed medium-power transformer.

Solid and liquid components of this system may be tested before and after aging at various times and temperatures. Solid materials may be tested for dielectric strength, tensile strength, dissipation factor, degree of polymerization (DP), moisture content, and compression strength. Samples of the liquid can be subjected to the standard battery of tests, including dielectric strength, power factor, specific gravity, water content, dissolved gases, and viscosity.

5.6 High-temperature solid and wire insulation and their interaction with mineral oil and other high-temperature fluids

Mineral oil and other high-temperature insulating fluids have been investigated by the Insulating Fluids Subcommittee of the Transformer Committee, and appropriate IEEE documents have been prepared by that subcommittee. The interaction between solid insulation and the dielectric fluid in high-temperature transformers is addressed in this guide.

Experiments to determine the maximum temperature that can be allowed for aramid insulation impregnated with mineral oil have revealed negligible degradation up to 220 °C [B1]. Extensive testing has been done on the aramid base product in sealed containers immersed in mineral oil, with little or no degradation of the oil.

The interaction between the wire enamel and the dielectric fluid also requires examination. Considerable progress has been made over the years in developing wire enamels with higher operating temperatures. Approximately twice the insulation temperature class of conventional 105 °C materials was achieved by the introduction of polyimide- and polyamide-imide-type enamels. Table 2 shows the temperature classes of various enamels that can be used in liquid-filled transformers.

Table 2—Enamel temperature classes

Magnetic wire enamel	Insulation temperature class (°C)
Modified polyvinyl formal resin	105
Epoxy	130
Polyesteramide-imide	200
Pyre-ML polyimide	220

Other magnetic wire enamels may be applicable to liquid-immersed transformers, but should first be tested per IEEE Std C57.100-1986, as discussed in 5.4 of this guide.

6. Loading guides for high-temperature transformers

IEEE Std C57.91-1995 provides information for the calculation of the loss of life of the transformer from recorded temperature cycles taken over an extended time period. Similar information will eventually be compiled for aramid and other high-temperature insulation materials.

The user may estimate the loss of life for aramid-based materials in transformer oil using the Arrhenius curve in Figure 3 and the basic procedures outlined in IEEE Std C57.100-1986. The ESEERCO [B1] aging data were obtained from sealed tubes aging in mineral oil. The tubes contained aramid paper, silicon steel,

copper, and wire enamel, and were tested at temperatures of 200 °C, 220 °C, 235 °C, and 250 °C. The curve of insulation life was developed from those tests where retained tensile strength was less than 90%. Obtaining reliable extrapolation of the data requires the retention of tensile strength in the range of 20% to 80%. Very few data points in this study were in this range, which made the extrapolation of the insulation life difficult. The equation for aramid material in oil, based on the ESEERCO data, is

$$\text{Life (hours)} = \varepsilon^{(B/\theta - A)} \qquad (2)$$

where

A	is 19.917,
B	is 14 300,
ε	is the base of the natural logarithm,
θ	is 273 + (MHCT-10), in °C,
MHCT	is the maximum hottest conductor temperature, in °C.

NOTE—The constants will be different for other materials.

The operating experience accumulated on high-temperature transformers designed, built, and put in service since 1979 may also be used as the technical database broadens. So far, experience with high-temperature transformers has revealed no failures attributed to excessive heating and aging of the insulation system.

7. Description of high-temperature transformers

The description is similar to that for cellulose-insulated transformers, except that some special requirements are added because of the high-temperature operation. The manufacturer should define the allowable winding hottest-spot and top oil temperature limits based on the demonstrated life expectancy of the insulation system. The manufacturer should also identify any special requirements or limitations on bushings, load tap changer, de-energized tap changer, oil expansion, or other auxiliary equipment that may affect transformer loading or life expectancy.

In the case of failed transformers that are rebuilt and uprated in capacity (MVA), the repairer should pay special attention to the thermal and/or ampere ratings of the following items:

— Maximum top oil temperature
— Bushings
— Load tap changer
— De-energized tap changers
— Current transformers
— Series transformers
— Preventative auto-transformers (LTC)
— Lead cables
— Oil expansion
— Pressure in sealed units
— Cooling capacity
— Stray flux heating
— Circuit breakers

It should be recognized that these items might limit the uprate capacity of the repaired transformer.

7.1 Transformers with hybrid high-temperature insulation systems

7.1.1 Characteristics and applications

These transformers are employed as units operating mainly at or below rated load level, which corresponds to that of the traditional cellulose-insulated transformer. However, they have the ability to withstand a considerable overload during contingency conditions, without a significant reduction of their life expectancy. Obviously, the load losses dissipated under overload conditions are high, but these losses occur only during the relatively short time of operation in such an emergency mode.

If mineral oil is used as the insulating liquid, the top oil temperature should not exceed 105 °C per IEEE Std C57.91-1995, Table 8, during normal loading, or 110 °C for loading above the nameplate rating. These limits are recommended to maintain the thermal integrity of the auxiliary equipment and components such as bushings, paint, control wiring, gaskets, current transformers, series transformers, and tap changers.

Benefits related to the specific transformer application can be expected to include the following:

a) Lower total weight
b) Same physical size, capable of operating at continuous overload
c) Reduced physical size, designed for installation in a limited space

NOTE—“Same” and “reduced” with respect to a cellulose insulated unit having the same nameplate rating, but at 65 °C rise.

7.1.2 Technical specifications

The technical specifications for a hybrid insulated transformer emphasize the requirement for a negligible loss of life of the insulation caused by a temporary operation at higher than normal temperatures.

7.2 Transformers with high-temperature insulation systems

7.2.1 Characteristics and applications

Transformers with an insulation system of all high-temperature material in mineral oil may be used for special applications, such as traction units, vault installations, and furnace transformers. Because they have no low-temperature solid insulation material anywhere inside the transformer, they can operate at even higher winding temperatures than a hybrid unit. The maximum winding temperature would depend on the material capability.

8. Nameplate information

For a given nameplate rating, the following data should be supplied on the transformer’s nameplate:

AWR/MTOR/MKR/MHCR

also abbreviated as

$\Delta\theta_{w}/\Delta\theta_{to}/\Delta\theta_{hk}/\Delta\theta_{h/a}$

where

AWR	is the average winding rise,
MTOR	is the maximum top oil rise,
MKR	is the maximum cellulose rise (applies to hybrid design only),
MHCR	is the maximum hottest conductor rise.

NOTE—“Rise” indicates temperature rise above ambient, with a maximum ambient of 40 °C.

This information can be used for the operation of transformers with a hybrid high-temperature insulation system.

The specifications for cellulose-insulated transformers designed for 65 °C average winding rise, and for hybrid high-temperature transformers designed for higher average winding rises, are different when it comes to the following:

— Winding hottest-spot rise over ambient temperature ($\Delta\theta_{h/a}$)
— Winding maximum hottest-spot temperature (θ_h)

The specification is the same for the following:

— Maximum ambient temperature (θ_a)
— Maximum top oil temperature (θ_{to})
— Maximum cellulose temperature (θ_{hk}) (if a hybrid design)

It should be noted that in a 65 °C cellulose design, MKR = MHCR = 80 °C. In a hybrid high-temperature insulation design, the MHCR will depend on the temperature capability of the insulation material used on the conductor.

9. Heat run test and average winding temperature

The standard method of finding the average winding temperature (using resistance measurements extrapolated back to the instant of shutdown) may not be accurate enough for use in testing a high-temperature transformer. This is because of the higher rate of winding temperature decay that will occur when starting the shutdown period at a temperature higher than that of a 65 °C rise cellulose unit. Such an inaccuracy would also affect calculated values of winding hottest-spot temperature if they are determined by adding a gradient to the average winding temperature. Until accumulated experience permits, an experimental confirmation of the calculated value of hottest-spot temperature may be required.

Annex A

(normative)

Gas analysis

IEEE Std C57.104-1991 describes the determination of dissolved gases generated by thermal or electrical faults and provides guidance for interpreting gas concentration in terms of serviceability of a conventional mineral oil/cellulose-insulated transformer. The concentration limits and fault identification criteria represent a consensus of many European and North American transformer manufacturers and operators. Similar data have yet to be developed for transformers insulated with high-temperature materials. Until such data have been accumulated for transformers insulated with high-temperature materials, IEEE Std C57.104-1991 should be used with caution to analyze gases from these transformers. This is especially important because limiting concentration, key gases, and gas ratios for hybrid cellulosic/aramid/oil or pure aramid/oil systems may be quite different than for a cellulosic/mineral oil insulation system, and may lead to erroneous conclusions as to either fault type or progress.

In order to use this important analytical tool with transformers insulated with high-temperature materials, it is important to understand the gases that would evolve from these insulation materials under similar conditions. While it is beyond the scope of this guide to specify the precise method for determining this information, a number of techniques have been used. As an example, a thermal gravimetric analysis (TGA) can be used to determine weight loss versus temperature, and a combination gas chromatograph/mass spectrometer (GC/MS) can be used to determine the specific gas types. These types of techniques could help identify the temperature at which a new material will start to break down, and what gases would be given off. For example, cellulose insulation begins to decompose at 120 °C, and the principal breakdown products are water, carbon dioxide, and carbon monoxide. As a second example, aramid materials decompose at temperatures in excess of 350 °C, and the principal breakdown products are carbon dioxide and various hydrocarbons. It is also important to verify the initial breakdown product, in order to use this information to monitor life using existing methods, as detailed in IEEE Std C57.104-1991.

A.1 Dissolved gas-in-oil for transformers insulated with high-temperature materials

To date, high-temperature insulation materials have been used in liquid-immersed power transformers as follows:

a) As the insulation in the hottest portions of a liquid-immersed transformer with a hybrid insulation system

b) For all components in an insulation system in liquid-immersed transformers, such as traction transformers, with high-temperature fluids

Because this application guide involves primarily the first situation, these comments were developed around the hybrid insulation system.

Users of liquid-immersed transformers insulated with high-temperature materials have concerns about how to monitor their transformer life in a manner similar to that used for traditional transformers, as discussed in IEEE Std C57.104-1991. These concerns typically revolve around the following two situations:

— What is the initial breakdown product for these high-temperature materials, at what conditions would it be generated, and what should the alarm points be for this breakdown product in the gas-in-oil sample?

— What gases are evolved during arcing, and what should the alarm point be for these gases?

A.2 Thermal aging of an aramid/cellulose/mineral oil hybrid system

A hybrid insulation structure uses aramid papers and transformerboards in the most thermally stressed locations within the mineral oil–immersed transformer, and continues to utilize cellulosic insulation components in those locations where the temperatures are below 120 °C at rated loads. The portion of the insulation system that is aramid material is thus quite small. Also, the low-temperature materials (cellulose and mineral oil) would be expected to break down well before the aramid materials, because in the hybrid high-temperature insulation system, the temperature of the aramid is well below its thermal capability.

For these reasons, the expectation is that the gas-in-oil analysis for a hybrid insulated transformer would be quite similar to that of a traditional, cellulose/mineral oil–insulated transformer. In fact, the transformer should show less of a gassing tendency because of the absence of breakdown products under normal aging of the aramid material. As discussed earlier in this guide, winding hottest-spot temperatures up to 190 °C have been used in these hybrid insulated transformers. Data from a TGA analysis shows that aramid materials give off no gases at temperatures they would be expected to experience during normal, or even emergency, loading.

As confirmation of this expectation, data are being collected on transformers that have a hybrid insulation system. Two tables show the current data that have been collected. Table A.1 shows the gas-in-oil data for several operating mobile transformers, while Table A.2 shows similar data for substation transformers.

Table A.1—Gas-in-oil data for mobile transformers

Gas-in-oil data (ppm vol/vol)	Minimum	Average	Maximum	Number of samples
Hydrogen	0	10	49	46
Oxygen	923	9318	23 480	23
Nitrogen	43 800	81 578	142 885	10
Methane	0	6	53	46
Carbon monoxide	0	83	555	46
Ethane	0	2	7	46
Carbon dioxide	73	654	2141	46
Ethylene	0	5	22	46
Acetylene	0	2	39	46

Table A.2—Gas-in-oil data for substation transformers

Gas-in-oil data (ppm vol/vol)	Minimum	Average	Maximum	Number of samples
Hydrogen	0	7	39	11
Oxygen	2769	9292	23 980	11
Nitrogen	87 670	110 154	124 195	8
Methane	0	5	13	11
Carbon monoxide	0	31	91	11
Ethane	0	3	12	11
Carbon dioxide	281	821	1682	11
Ethylene	0	1	8	11
Acetylene	0	0	0	11

A.3 Generation of gas under arcing conditions

There is an interest in determining what happens to the high-temperature material under arcing conditions. While this is a legitimate concern, the potential is limited for a gas-in-oil analysis to show what is happening to the high-temperature material. In a power transformer, arcing can occur in many locations, most of which would not be insulated with high-temperature materials in a hybrid design. An arc formed in the area of the conductors is one location where high-temperature materials are used within the structure.

In general, it can be very misleading to obtain off-gassing data on individual materials that are then used to estimate what would happen if all materials were together in a complete insulation system. A single material may produce a given compound when treated alone, but the quantity of this gas may be insignificant when taken together with other materials in a system. In addition, the temperatures required to generate these gases may be so high that the other materials would be severely compromised long before the gases develop. The most useful data are those that would be generated from an actual transformer experiencing a known problem.

Annex B

(informative)

Bibliography

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[B5] U.S. Federal Register, Vol. 38, No. 237, Dec. 11, 1973.